CHAPTER 14

ELECTRIC MOTORS

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14.1 INTRODUCTION

Electric motors play a very important part in supplying power for all types of domestic and industrial applications. Their versatility, dependability, and economy of operation cannot be equaled by any other type of a power unit. Many types of motors are available and are, therefore, classified in various ways. There are general purpose, special purpose, and definite purpose types of motors. Motors are also classified according to the type of electricity they require; a motor may operate on direct current (DC) or alternating current (AC). If AC, the motor may be of a single or polyphase design.

This chapter contains failure rate models that apply to all electric motors which can be used to support the development of mechanical equipment and provide a reliability estimate for a new design, proposed design modification, or application other than verified specification parameters. The models are intended to focus attention on further design analysis which should be accomplished to assure the allocated reliability of the motor in its intended operational environment.

14.2 CHARACTERISTICS OF ELECTRIC MOTORS

14.2.1 Types of DC Motors

DC motors are classified as either series-wound, shunt-wound, or compound-wound. In the series-wound motor, field windings which are fixed to the stator frame, and the armature windings which are placed around the rotor, are connected in series so that all current that passes through the field windings also passes through the armature windings. In the shunt-wound motor, the armature and field are both connected across the main power supply (in parallel) so that the armature and field currents are separate. The compound-wound motor has both the series and shunt field windings. These may be connected so that the currents are flowing the same direction in both windings, called "cumulative compounding", or so that the currents are flowing in opposite directions, called "differential compounding".

14.2.2 Types of Polyphase AC Motors

The most extensively used polyphase motors are the induction type. The "squirrel cage" induction motor has a wound stator connected to an external source of AC power and a laminated steel core rotor with heavy aluminum or copper conductors set into the core around its periphery while being parallel to its axis. These conductors are connected together at each end of the rotor by a heavy ring, providing closed paths for currents induced in the rotor to circulate. The rotor windings are not connected to the power supply.

The wound-rotor type of induction motor has a squirrel cage and a series of coils set into the rotor which are connected through slip-rings to external variable resistors. By varying the resistance of the wound-rotor circuits, the amount of current flowing in the circuits, and therefore the speed of the motor, can be controlled. Induction motors are manufactured with a wide range of speed and torque characteristics.

The synchronous motor is the other type of polyphase AC motor. Unlike the induction motor, the rotor of the synchronous motor is connected to a DC supply which provides a field that rotates in step with the AC field in the stator. The synchronous motor operates at a constant speed throughout its entire load range, after having been brought up to this synchronous speed. This speed is governed by the frequency of the power supply and the number of poles in the rotor.

14.2.3 Types of Single-Phase AC Motors

Most of the single-phase AC motors are induction motors distinguished by different arrangements for starting. Single-phase motors are used in sizes up to about 7 1/2 horsepower for heavy starting duty, chiefly in home and commercial appliances for which polyphase power is not available.

The series wound single-phase motor has a rotor winding in series with the stator winding as in the series-wound DC motor. Since this motor may also be operated on direct-current, it is called a "universal motor". The series wound motor has a high starting torque and is used in vacuum cleaners, sewing machines, and portable tools. In the capacitor-start single-phase motor, an auxiliary winding in the stator is connected in series with a capacitor and a centrifugal switch. During the starting and accelerating period the motor operates as a two-phase induction motor. At about two-thirds full-load speed, the auxiliary circuit is disconnected by the switch and the motor then runs as a single phase induction motor.

In the capacitor-start, capacitor-run motor, the auxiliary circuit is arranged to provide high effective capacity for high starting torque and to remain connected to the line, but with reduced capacity during the running period. In the single-value capacitor or capacitor split-phase motor, a relatively small continuously-rated capacitor is permanently connected in one of the two stator windings and the motor both starts and runs like a two-phase motor.

In the repulsion-start single-phase motor, a drum-wound rotor circuit is connected to a commutator with a pair of short-circuited brushes set so that the magnetic axis of the rotor winding is inclined to the magnetic axis of the stator winding. The current flowing in this rotor circuit reacts with the field to produce a starting and accelerating torque. At about two-thirds full load speed the brushes are lifted, the commutator is short circuited and the motor runs as a single-phase squirrel-cage motor. The repulsion motor employs a repulsion winding on the rotor for both starting and running. The repulsion-induction motor has an outer winding on the rotor acting as a repulsion winding and an inner squirrel cage winding. As the motor comes up to speed, the induced rotor current partially shifts from the repulsion winding to the squirrel cage winding and the motor runs partly as an induction motor.

In the split-phase motor, an auxiliary winding in the stator is used for starting with either a resistance connected in series with the auxiliary winding (resistance-start) or a reactor in series with the main winding (reactor-start). The split-phase motor is used in refrigerators, air conditioners, freezers, and other compressors involving high starting loads.

14.3 ELECTRIC MOTOR FAILURE MODES

The most prominent failure mode for a motor is shorting of the motor winding. Typical failure modes and their failure causes and effects are listed in Table 14-1. For additional information on individual parts of the motor, the particular chapter for that part should be reviewed as shown below:

1. Bearings (See Section 7.4)
2. Windings (See Table 14.1 below and Section 14.5)
3. Brushes (See Table 14.1 below)

4. Armature (shaft) (See Section 20.2)
5. Stator Housing (casing) (See Table 14.1 below)

Table 14-1. Electric Motor Failure Modes

FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT
- Open winding - Shorted winding	- Excessively high temperature	- Motor won't run - Sparking at brushes
- Worn bearing: -- spalling --creeping or spin	- Poor lubrication - Contamination - Overloading or high temperature	- Noisy - Heat build-up - Armature rubbing stator - Seized
- Cracked housing	- Fatigue - External shock - Vibration	- Leakage of dust into motor - Shorted or seized
- Sheared armature shaft - Cracked rotor laminations	- Fatigue - Misalignment - Bearing failure	- Seized - Armature rubbing stator
- Worn brushes	- Improper maintenance - Contamination - High temperature - Low atmospheric humidity - Improper contact pressure	- Excessive sparking - Chatter or hissing noise - Motor runs too fast or too slow under load
- Worn sleeve bearing	- Excessive load (belt tension) - Frequent starts and stops under heavy loads - Poor lubrication	- Seized - Noisy - Heat build-up - Armature rubbing stator

Additional details of failure modes for those components of a motor such as bearings and shafts are included in the applicable chapters of this Handbook.

14.4 MODEL DEVELOPMENT

The failure rate model included in this section is based upon identified failure modes of individual parts. The model developed is based on a fractional or integral horsepower AC type motor, although it will be general enough to be applied to most motors.

The reliability of an electric motor is dependent upon the reliability of its parts, which may include: bearings, electrical windings, armature/shaft, housing, and brushes. Failure mechanisms resulting in part degradation and failure rate distribution (as a function of time) are considered to be independent in each failure rate model. The total motor system failure rate is the sum of the failure rates of each of the parts in the system:

$$\lambda_M = \lambda_{BE} + \lambda_{WI} + \lambda_{BS} + \lambda_{AS} + \lambda_{ST} + \lambda_{GR} \quad \textbf{(14-1)}$$

Where: λ_M = Total failure rate for the motor system, failures/million hours

λ_{BE} = Failure rate of bearings, failures/million hours (See Chapter 7)

λ_{WI} = Failure rate of electric motor windings, failures/million hours (See Section 14.5)

λ_{BS} = Failure rate of brushes, 3.2 failures/million hours/brush (Reference 68)

λ_{AS} = Failure rate of the armature shaft, failures/million hours (See Chapter 20, Section 20.4)

λ_{ST} = Failure rate of the stator housing, 0.001 failures/million hours (Reference 68)

λ_{GR} = Failure rate of gears, failures/million hours (See Chapter 8)

14.5 FAILURE RATE MODEL FOR MOTOR WINDINGS

The life expectancy of a motor winding is primarily dependant on its operating temperature with respect to the permitted temperature rise of the winding. The temperature rise of the winding (and the insulation materials) is a function of the design of the motor. The insulation materials age over time and this aging process is directly related to temperature. Eventually, the materials lose their insulating properties and break down causing one or more short circuits.

Temperature rise occurs in a motor due to the losses that occur in the motor, normally copper and iron losses. The temperature inside the motor will depend on how effectively this heat can be removed by the cooling system of the motor. The difference between the internal and external temperatures is dependent on the thermal gradient and this difference is normally quite low.

The electric motor windings failure rate, λ_{WI}, is derived by Equation (14-2):

$$\lambda_{WI} = \lambda_{WI,B} \bullet C_T \bullet C_V \bullet C_{alt} \quad \textbf{(14-2)}$$

Where: $\lambda_{WI,B}$ = Base failure rate of the electric motor windings, failures/million hours (See Section 14.5.1)

C_T = Multiplying factor which considers the effects of ambient temperature on the base failure rate (See Section 14.5.2 and Figure 14.1)

C_V = Multiplying factor which considers the effects of electrical source voltage variations (See Section 14.5.3)

C_{alt} = Multiplying factor which considers the effects of operation at extreme elevations (See Section 14.5.4 and Table 14-3)

14.5.1 Base Failure Rate

$\lambda_{WI,B}$ is the base failure rate of the specific motor winding as supplied by the motor manufacturer. The winding will usually be specified in terms of expected life. The base failure rate is then:

$$\lambda_{WI,B} = \frac{1.0\,x\,10^6}{L_I} \quad \textbf{(14-3)}$$

Where: L_I = Expected winding life, hours

If a manufacturer's winding life is not available, a winding life of 20,000 hours can be expected from most manufacturers (References 28 and 89). The multiplying factors for Equation (14-2) are described in the following paragraphs.

14.5.2 Temperature Multiplying Factor

Heat is the primary limiting factor of motor windings. Heat causes the windings to age and deteriorate, so after time they break down and lose their insulation quality. When this happens, the related electrical components "short" and the motor burns out.

The manufacturer's rating of a motor based on insulation and expected life is provided in 25^{o} increments. The temperature rating for each class of insulation is defined as the maximum temperature at which the insulation can be operated to yield the rated winding life. The temperature rating for the various classes of insulation is shown in Table 14-2.

Table 14-2. Motor Insulation Ratings

Insulation Class	Temperature Rating	Maximum Ambient Temperature	Anticipated Temperature Rise	Hot Spot Allowance
A	105^{o} C	40^{o} C	60^{o} C	5^{o} C
B	130^{o} C	40^{o} C	85^{o} C	5^{o} C
F	155^{o} C	40^{o} C	110^{o} C	5^{o} C
H	180^{o} C	40^{o} C	135^{o} C	5^{o} C

Under normal operating conditions, the insulation material used in the windings of electric motors is generally reliable, thereby making the windings themselves a reliable component. The life of any given insulation material depends on the degree of heat to which it is exposed.

The winding temperature is determined by measuring both the ambient and the hot temperature resistances of the windings. The resistance measurement gives an average temperature which is more representative than spot measurements with a thermometer. This method has become standard because of the dimensional restrictions of so many motor designs, which prevent the use of thermometers.

The equation for determining the motor winding temperature from resistance readings is as follows:

$$T_R = \frac{R_H - R_C}{R_C}(235 + T_C) \qquad \textbf{(14-4)}$$

Where: T_R = Temperature Rise, ^{o}C

R_H = Hot winding resistance, ohms

R_C = Cold winding resistance, ohms

T_C = Ambient temperature, ^{o}C

The winding life increases by a factor of 2 for every 10 degree of rating. Therefore if manufacturer provides a motor with a insulation class F for a B class environment, the motor can be expected to last twice as long.

The correction factor for the motor winding temperature is given by:

$$C_T = k \ x \, 10^{2357\left[\frac{1}{T_r + 273} - \frac{1}{T_o + 273}\right]} \qquad \textbf{(14-5)}$$

Where: T_r = Temperature rating of windings, ^{o}C (See Table 14-2)

T_o = Internal motor temperature during operation, ^{o}C

k = 1.0

Figure 14.1 shows the effect of temperature on failure rate for various classes of motors.

14.5.3 Voltage Multiplying Factor

The motor horsepower rating on the nameplate may not necessarily indicate the motor's maximum capacity. The motor is often designed with extra capacity built in to allow for variations. A motor will operate successfully when the variation in voltage does not exceed ±10% of normal. A failure rate multiplying factor can be established for those situations when the actual voltage exceeds rated voltage:

For $V_A > V_R$:

$$C_V = 1.0 + 0.5\left(\frac{V_A - V_R}{V_R}\right) \qquad \textbf{(14-6)}$$

Where: V_R = Rated Voltage

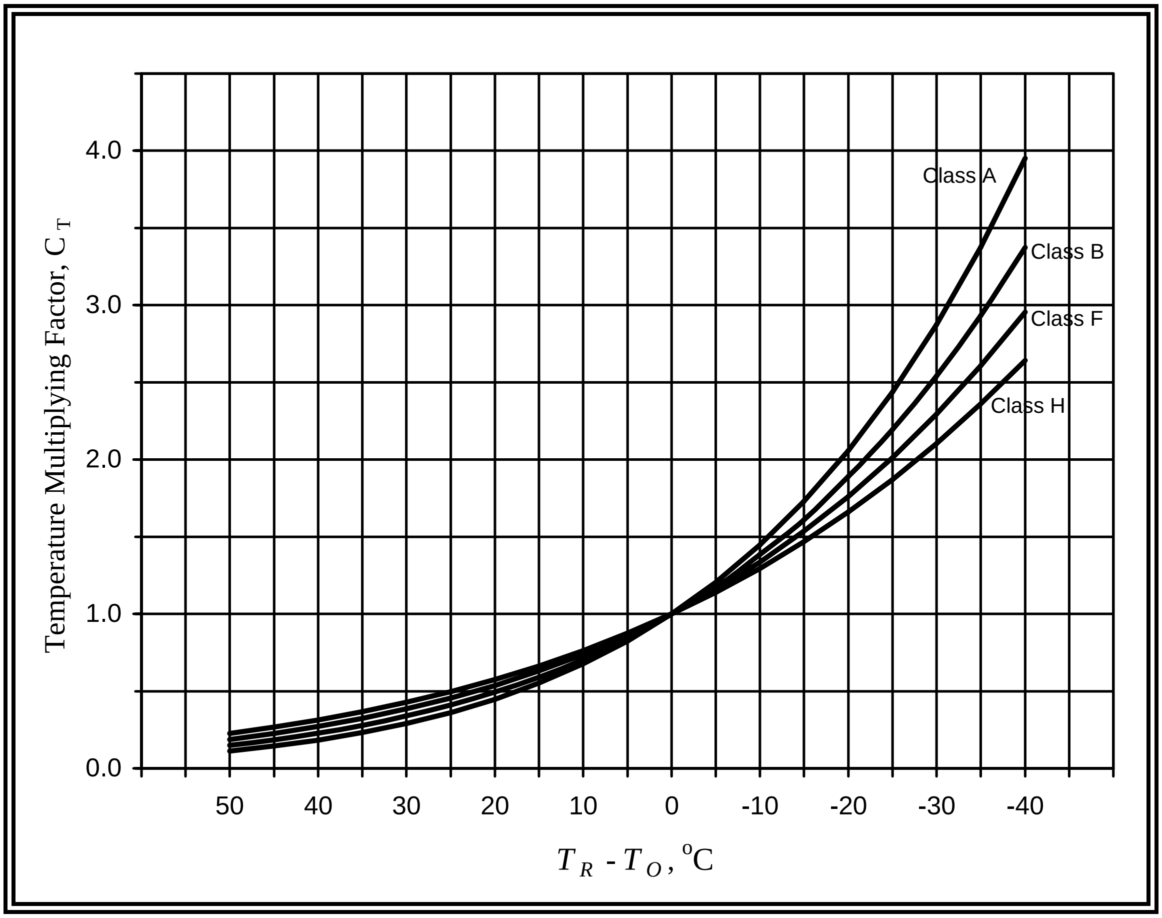
V_A = Actual Voltage

For $V_A \leq V_R$:

$$C_V = 1.0 \qquad \textbf{(14-7)}$$

14.5.4 Altitude Multiplying Factor

The influence of altitude on the life of a fan-cooled motor may be tabulated based on a 50% reduction in life for every 10^{o}C increase in sea level motor temperature rise. Table 14-3 is a tabulation of failure rate multiplying factor, C_{alt}, for altitude/temperature conditions applicable to fan-cooled motors which are not enclosed. For totally enclosed motors, altitudes to 60,000 feet will not influence life as compared to sea level and C_{alt}, in this case, will be equal to 1.0.



$$C_T = k \ x \, 10^{2357\left[\frac{1}{T_r + 273} - \frac{1}{T_o + 273}\right]}$$

Where: T_r = Temperature rating of windings, °C (See Table 14-2)

T_o = Internal motor temperature during operation, °C

k = 1.0

Figure 14.1 Temperature Multiplying Factor, C_T

Table 14-3. Multiplying Factor C_{alt} for the Influence of Altitude on Motor Life for Fan-Cooled Motors

ALTITUDE (ft x 1000)	SEA LEVEL MOTOR TEMPERATURE RISE				
	20^{o}C	30^{o}C	40^{o}C	50^{o}C	60^{o}C
Sea level	1.0	1.0	1.0	1.0	1.0
25	1.0	1.0	1.0	1.0	1.0
30	1.0	1.0	1.0	2.0	4.0
40	1.0	2.0	4.0	8.0	16.0
50	4.0	8.0	16.0		
60	16.0				

14.6 REFERENCES

28. MIL-HDBK-217, "Reliability Prediction of Electronic Equipment"

68. Anderson, Edwin P., Electric Motors Handbook, Bobbs-Merrill Co., Inc., NY, NY 1983

89. SINTEF Industrial Management, "OREDA Offshore Reliability Data", 4th Edition, 2002

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